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THE USE OF CHARGE COUPLED DEVICES IN COMPACT SONAR SYSTEMS

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1. INTRODUCTION

The performance of active sonar systems is limited by interfering sources of noise and reverberation and to combat these the sonar designer has control of three independent parameters namely array size, signal bandwidth and signal pulse duration.

For large ship-borne sonar applications, it is possible to implement the required signal processing and beam forming functions using digital techniques (Ref 1). However, in the case of smaller sonars, particularly with smaller arrays, where to meet performance specifications it is necessary to go to larger signal bandwidths, the adoption of digital techniques using present day devices still imposes unacceptable limits on the processing performance available (Ref 2). Fortunately, the charge-coupled device (CCD) (Ref 3) has appeared on the scene and seems ideally suited to the small array applications for both stabilised beam forming and matched-filter signal processing. The CCD accepts analogue signal samples directly and performs the necessary operational and storage functions at speeds in excess of that required for sonar. In addition, the CCD, based on MOS technology, has the simplicity, economy, and lower power consumption that this technology affords and this combined with the direct analogue approach makes it suitable for the smaller, higher bandwidth sonars.

2. CCD BEAM FORMING AND STEERING

To steer the beam formed by a hull-mounted fixed array requires the introduction of delay elements between each transducer in the array. If the delay of each element can be varied and controlled as a function of the ship's motion then the direction of the beam can be stabilised in space. In the case of a CCD delay line the delay is simply varied by varying a clock frequency governing the speed of charge transfer through the device. The CCD is, therefore, ideally suited to this type of beam forming and steering where clock frequency generation provides a convenient digital interface with a controlling computer.

2.1 Receive Beam Forming

Figure 1 shows how a receive beam is formed from a column of transducers using a CCD delay line. To steer the beam through the angle θ, requires a delay line with time delay and summing capabilities as shown. Such a device has been designed and made by RSRE, Malvern, and is referred to as a Time Delay and Integrate (TDI) device (Ref 5). The prototype device is a P-channel CCD using a three-phase polysilicon technology, and has sixteen inputs. The range of time delays, and hence possible beam-steer angles, that can be achieved by the TDI is a function of the minimum and maximum clocking frequencies. The minimum clock frequency is set by the Nyquist minimum sampling rate criterion, and the highest signal frequency being sampled. The highest clock frequency is set by an acceptable level of smearing of the sample charges being clocked through the TDI. In practice, the maximum value of θ is limited to about 30^{o}, the limit being set by acceptable levels of side-lobes. At frequencies below 100 kHz existing devices will steer beams to within 1^{o} of the straight-ahead direction.

An experimental four beam steering system based on the preceeding design features has been built and tested at sea. Typical beams formed by this system, where the steering angle is under direct digital control, are shown in Figures 2 and 3. Although the facility is available, it is obvious from the plots that no element 'shading' has been applied.

2.2 Transmit Beam Forming

Figure 4 shows how a beam is formed in the transmit mode. Here a signal is sampled and clocked along a CCD delay line, and equally spaced taps sense the charge packets as they pass. By means of a band-pass filter on each tap output, output signals are reconstituted, and each tap output signal has a phase relationship with all other tap output signals which is a function of the delay line clock frequency.

An experimental four beam steering system has been produced which complements the previously described four beam receive system. The corresponding transmit beams obtained in measurements at sea are shown in Figures 5 and 6.

3. CCD SIGNAL PROCESSING

The sonar signal processor uses a combination of active and passive modes in order to aid the detection and classification of targets. The signal processor usually consists of a matched filter for active ranging, and a spectrum analyser for active Doppler and passive operation. Matched filters can be implemented using a wide variety of techniques, but for sonar applications the choice becomes limited, because processing involves signal sotrage times ranging from several tens of milliseconds to a second or so in some cases. In addition, because of the difficult underwater environment and limited performance parameters, it is a distinct advantage to introduce a considerable degree of flexibility into the processing system in order to be able to optimise the performance for a given set of conditions (Ref 4).

3.1 Parameter Values and Sonar Performance

For a given array size and signal bandwidth, the reverberation-limited performance of a sonar system may be represented in terms of detection range and operating frequency as, for example, line RL(B) in Fig 7, where the performance increases with increasing frequency due to reduced beamwidths.

For a given transmitted power, the noise-limited performance of a system is governed by the signal pulse duration, T, and noise-limited performance may also be represented in Fig 7 by a line such as $NL(T_1)$. $NL(T_1)$ in this case corresponds to a simple energy detector system, using a pulse duration case $T_1 = 1/B$ to achieve a performance consistent with the reverberation-limited case RL(B). The performance decreases with increasing frequency as shown due to an increase in attenuation, and point A represents the maximum performance achievable with such a simple system, where the optimum balance is struck between potential reverberation and noise-limited performance.

3.2 The Advantage of Correlation Processing

It can be seen from Fig 7 that to exploit further the potential reverberation performance of a system as represented by RL(B), there is a need to go to higher operating frequencies and to improve the noise-limited performance to an extent such as line $NL(T_2)$ in the figure. This can only be achieved by adopting correlation or pulse compression techniques which make it possible to use a signal bandwidth, B, to retain the reverberation-limited performance RL(B) whilst transmitting a much longer pulse length than the reciprocal of the bandwidth ($T_2 >> 1/B$) to achieve the required noise-limited performance. In practice, improvements in detection range of the order of 30% over the simple energy detector system are readily achieved by this means.

3.3 The Effect of Limited Array Size

When the array size is limited it becomes increasingly difficult to maintain a satisfactory reverberation-limited performance as, for example, in the case depicted in Fig 8 which shows the effects of an increase in surface reverberation as a result of an increase in sea state from SS1 to SS3. In this situation the detection range decreases by a factor of about 2 from point A to point C and there is no longer a satisfactory balance between reverberation and noise-limited performance. In fact, the potential noise-limited performance provided by pulse length T is contributing nothing to the performance at point C and in these circumstances it is worthwhile considering the possibility of exchanging some of this potential noise performance for an increased reverberation performance. For a given size and complexity of equipment there will be a limit to the BT product available for correlation processing and thus, keeping within a set, maximum value of BT, improved reverberation performance may be achieved by increasing B and reducing T appropriately. The effect of such a change by a factor of 3 is shown in Fig 8 where it can be seen that a comparatively small sacrifice in noise-limited performance has led to a dramatic improvement in reverberation performance to point D, recouping most of the lost detection range AC.

Here then is a strong case for correlation processing combined with a more flexible design approach to provide ready selection of combinations of operating parameters B and T thus enabling the performance to be optimised within the bounds of given equipment and environmental constraints.

Fortunately the development of charge coupled device transversal filters which can readily be used to implement correlation type receivers has enabled a system based on these principles to be constructed.

3.4 CCD Implementation of a Transversal Filter

The transversal filter is a general purpose sampled data, signal processing element. The filter performs a convolution of input samples with weighting coefficients which form the impulse response of the device. This may be expressed mathematically as

$$C(n) = \sum_{N} S(n-N)\ r_n$$

Such a filter with electrically programmable coefficients has been realised monolithically (Ref 6). The device architecture (figure 9) is simple and compact and is a direct realization of the transversal filter structure. The device has been implemented using linear charge transfer device and MOS component technology.

The signal register is formed from a tapped analogue CCD delay line. Signal information is represented by packets of charge which are transferred between closely spaced electrodes by applying a succession of pulsed voltages. Periodic tapping of the signal from the CCD delay line is achieved via capacitively-coupled sensing gates which are included at appropriate points within the CCD electrode structure.

Because the CCD signal register provides the necessary time-shift process a static analogue reference register is sufficient to supply the weighting values to the multipliers in parallel form. Weighting coefficients are altered or refreshed via a single multiplexed analogue input bus.

For general purpose signal processing, accurate multiplication of the signal and reference samples is required at each filter point. A novel multiplication arrangement has been developed around a single MOS transistor operating in the triode region which gives much improved performance over previous configurations. Matching requirements have been removed by time multiplexing and the entire multiplication and summing network is effectively chopper-stabilised at the system clock frequency.

3.5 Performance

A prime application of the programmable device in active sonar systems is as a matched filter, where the impulse response of the filter is chosen to be the time-reverse of the waveform to be detected. In such applications high Bandwidth-Time products are desirable. The maximum BT product that may be achieved is given by

$$(BT)_{max} = \frac{N}{2} \qquad (2)$$

where N is the number of filter taps.

When a CCD is used as a matched filter the ultimate limit on the number of filter points is determined by the charge transfer inefficiency (cti) of the device. Computer simulation indicates that performance is adequate providing the product

$$BT\varepsilon < 1 \qquad (3)$$

where ε is the cti value per filter stage. Thus for a typical ε per stage of 10^{-3} Bt's of 1000 may be used implying a total filter length of at least 2000 points.

When this work commenced, in 1977, CCD processing using aluminium gate technology limited device length to 64 points, with the possibility of producing 256 point devices in the future using polysilicon processing. For this reason 64 point devices were made available and a 256 point matched filter was constructed on a single printed circuit board. A sonar signal processor was made using these filter boards and was evaluated during shallow water sea trials. Recently a 256-point polysilicon device has been developed and evaluated in the laboratory, and these devices will be cascaded to make a 2048 point processor in the near future.

4. CCD BASED SONAR SYSTEM

The original 256 point CCD matched filter circuit boards form the basis of a flexible, linear amplitude sonar system (figure 10). The system consists of a captive array which can be suspended at depth from a trials vessel. Beamforming is achieved within the array unit, and beam outputs are routed to a ship-board variable gain receiver.

The gain of the receiver is microprocessor controlled and can be initially programmed by the operator, then released to adjust the gain adaptively on the basis of stored echo amplitude information from previous listening intervals. In this way non-linear amplitude agc type receivers are avoided. Waveforms to be transmitted by the array and CCD reference samples are also microprocessor generated. These waveforms may be selected to suit operational requirements.

The signal processor which follows the receiver operates on baseband signals, and therefore consists of inphase and quadrature channels. Each channel includes a 256 point CCD matched filter. The phase of the channel is determined by the reference samples.

The system has been tested at sea in Scottish Coastal Waters using a UK 'O' class conventional submarine as a target, and shallow water performance against a strong reverberation background has been demonstrated.

Conclusion

The requirement for flexible spatial and signal processing systems capable of optimising the reverberation limited performance within given operational constraints has been indicated. Experimental versions of CCD sonar beamforming and signal processing systems have been assembled and tested at sea. The results indicate that the CCD is well suited to sonar applications offering improved performance not only because of the flexibility of the processing but because the inherent power saving and compactness of the devices provide for more advanced post-processing.

5. ACKNOWLEDGEMENTS

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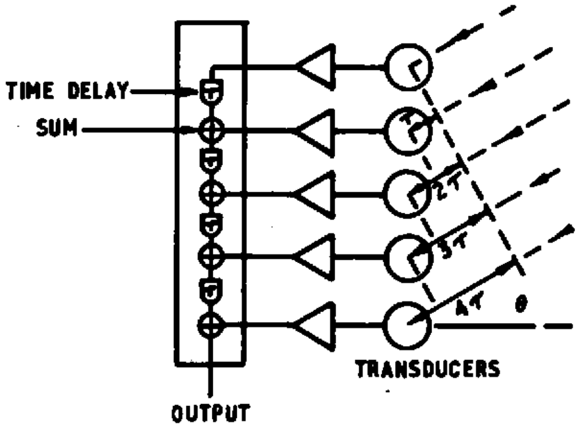
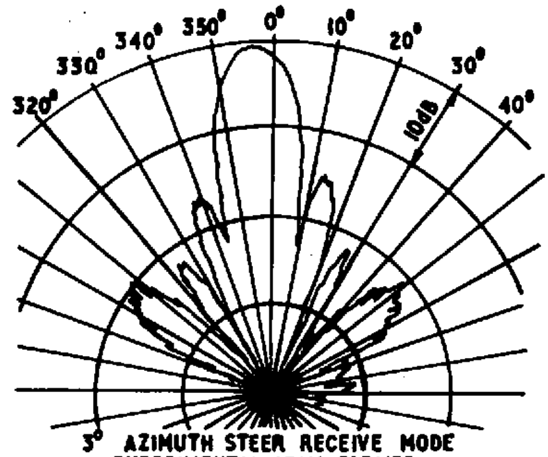
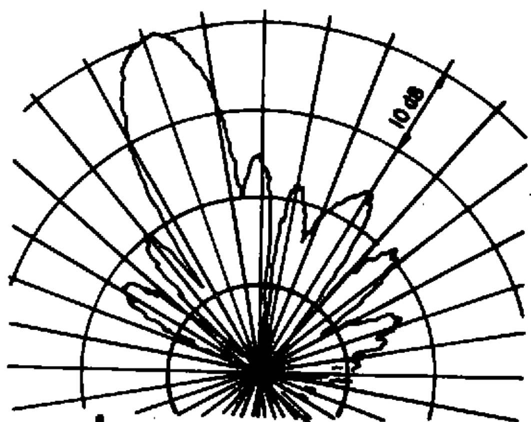


FIG. 1.



AZIMUTH STEER RECEIVE MODE
EXPERIMENTAL BEAM FORMER
FIG. 2.



20° AZIMUTH STEER RECEIVE MODE
EXPERIMENTAL BEAM FORMER
FIG. 3.

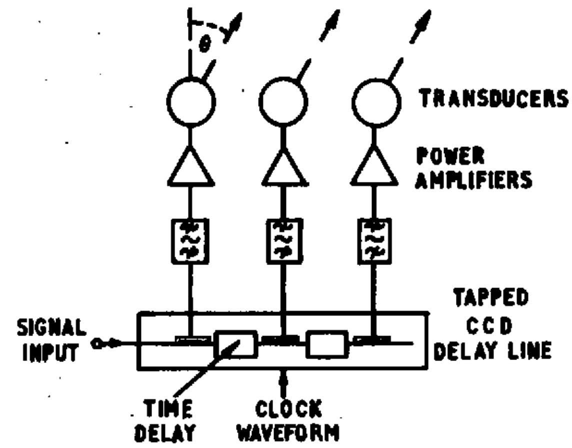
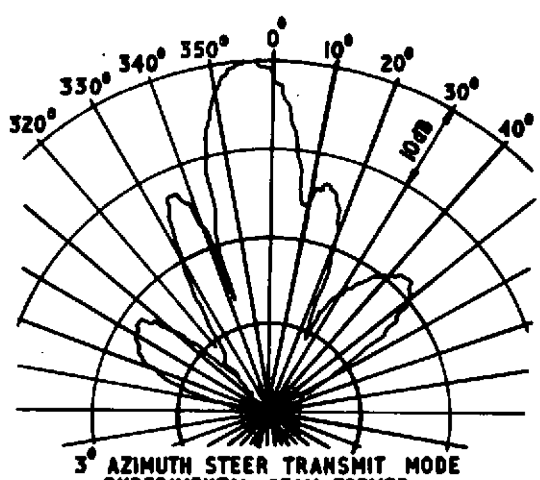
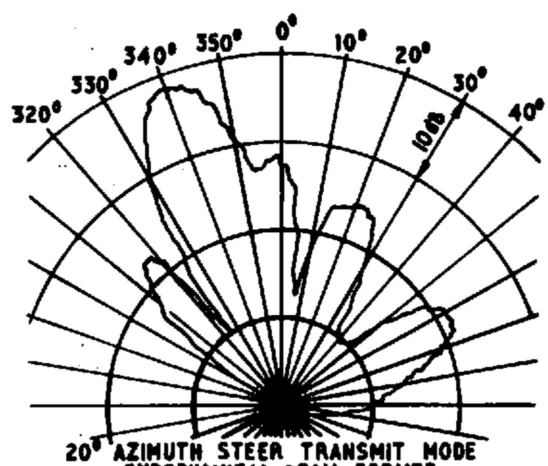


FIG. 4.



3° AZIMUTH STEER TRANSMIT MODE
EXPERIMENTAL BEAM FORMER
FIG. 5.



20° AZIMUTH STEER TRANSMIT MODE
EXPERIMANTAL BEAM FORMER
FIG. 6.

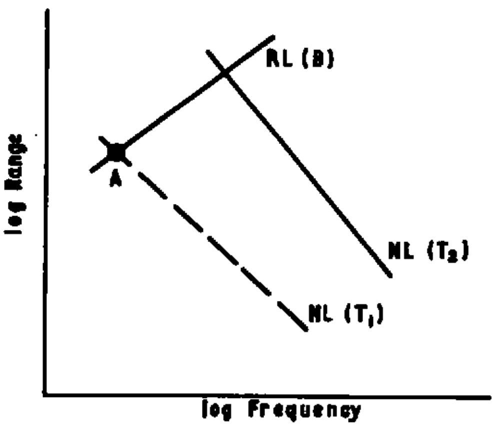


FIG.7. SONAR SYSTEM DETECTION RANGE AGAINST OPERATING FREQUENCY

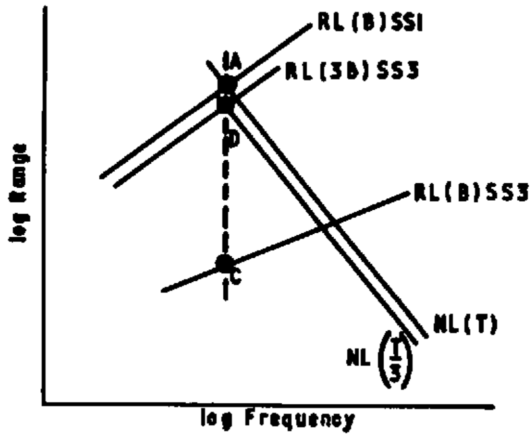


FIG. 8. THE EFFECTS OF SURFACE REVERBERATION ON PERFORMANCE

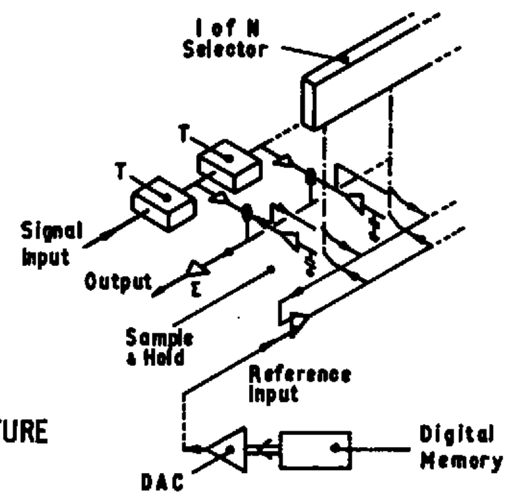


FIG.9. DEVICE ARCHITECTURE

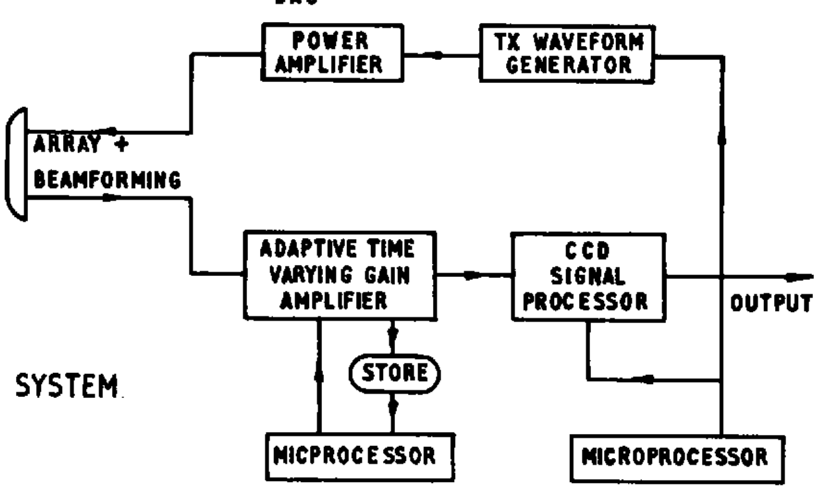


FIG. 10. SONAR SYSTEM